Fermilab

UPC No. 110

DIPOLE SKEW HARMONICS

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August 23, 1979

In this report we present results from an initial look at the effect of the skew harmonics present in the Tevatron dipoles on the large amplitude orbits attained during the extraction process. The values we have chosen to use for the calculations are based on the field measurements made on magnets 200 to 215 which yield the following values for the harmonic components:

$$\begin{aligned} a_1 &= 0.9 \pm 3.6 \\ a_2 &= -1.15 \pm 1.5 \\ a_3 &= -0.6 \pm 2.25 \\ a_4 &= -0.35 \pm 0.5 \end{aligned}$$

As more magnets are built and measured then these values will undoubtedly be modified to a certain extent but hopefully these changes will not effect the rather general conclusions arrived at in this report.

Skew terms in the dipole field will have the effect of coupling the horizontal and vertical orbits, transferring energy back and forth between the two modes. This process will be at its most severe during the extraction cycle when the horizontal amplitudes achieve their maximum value. Without applying any form of skew quadrupole correction then vertical orbit amplitudes in excess of 10 mms would occur, sufficient to seriously limit any form of extraction.

No analytic treatment of orbit coupling from skew fields during extraction exists. Theoretical treatments of orbit couplings generally rely on assuming some form of closed horizontal orbit and the approximation that the skew fields can be adequately described by a zeroth harmonic term. During one-half integer extraction both of these assumptions are somewhat dubious with the horizontal orbit amplitude increasing from turn to turn under the influence of a large 39th harmonic driving term. One fact which does emerge from the theoretical analysis, and presumably holds true during extraction too, is that any distributed series of skew correction elements should be split into at least two independently powered subsets (see, for example, Onhuma, TM-766) to optimize their efficiency. The distributed series of correction elements used in this report have not been optimized in this way and consequently the results we have obtained on the ability of a series of skew quadrupoles to correct the dipole skew fields should not be regarded as the best that could be achieved.

The method we select to look at the effect of the dipole skew fields is to use a ray-tracing computer program that integrates through each element in the ring. The field harmonics used for the dipoles consist of the Snowdon design fields for the normal harmonics together with skew harmonics generated randomly in Gaussian distributions according to the values given at the beginning of this report. The correction elements used to compensate for the dipole fields consist of skew quadrupoles and octopoles at the center of the regular lattice quadrupoles.

The first thing we have attempted to establish is the dominant skew harmonic in the dipole from the point of view of extraction. This we have accomplished by setting up on an extraction orbit, turning on the dipole skew harmonics individually and looking at the amplitude of the vertical orbit without attempting any orbit correction. The results show that the orbit coupling is dominated by the dipole skew quadrupole harmonic which produced a vertical amplitude of ~12 mms at a standard cell (β = 100 m) as opposed to ~0.75 mm for the skew sextupole, 2 mm for the skew octopole and <0.1 mm for the decapole term. These values were obtained using off-momentum orbits with $\Delta p/p$ = 0.05%.

The next step in the procedure was to attempt to correct for this orbit coupling by the addition of skew quadrupoles. We have looked at three different distributions of correction elements using the dipole skew quadrupole harmonic only. As a first attempt we placed elements at positions in the lattice defined by the positive horizontal amplitude maxima of the extraction orbit which permitted 15 correction elements (4 locations are already used by the extraction devices). This allowed the vertical orbit amplitude to be controlled to within ~3 mm throughout the extraction cycle. The next distribution of correction elements we tried was a simple extension of the first one and consisted of using lattice positions given by both the positive and negative hotizontal amplitude maxima of the extraction orbit, 37 locations in all. This distribution provided a slight improvement over the original one, containing the vertical amplitude to within ~2.5 mms. The third correction element distribution was made by placing skew quadrupoles at every defocussing quadrupole in a standard cell (90 locations). This produced a significant improvement over the other distributions with the vertical amplitude becoming no greater than 1 mm. The field strength of these correction elements is essentially defined by the systematic value of the dipole skew quadrupole harmonic and for the case in question here ($a_1 = 0.9 \times 10^{-4}$) a total integrated field strength of ~ 550 kG-in. at 1 in. is needed. With 90 correction elements this corresponds to ~ 15% of the available field strength. It is worth remarking at this point that increasing the strength of the correction elements does not improve the orbit stability. For a given dipole skew quadrupole systematic then there is a well-defined optimum value for the correction element field strength; too little and the dipoles still couple the orbits, too much and the correction elements themselves start to give orbit coupling.

Having established that we are able to provide satisfactory (if not optimal) orbit stability during the extraction cycle with respect to the dipole skew quad harmonic we then turned on the other skew terms using their systematic values only (i.e., $a_2 = -1.16 \pm 0$, etc.) and repeated the procedure as before. The vertical amplitude got worse (1.0 mm → 2.5 mm) indicating, not unsurprisingly, that skew correction quads work quite well at correcting skew quad harmonics but don't help much with the higher order terms. The addition of correcting skew octopoles at the same lattice locations as the skew quadrupoles proved necessary to cancel out the effect of the higher harmonics bringing the vertical amplitude back down to ~1.0 mm. The total integrated field strength for the octopoles is ~1000 kG-in. at 1 in.

The use of only the systematic values of the dipole harmonics defines only the zeroth harmonic of the skew field. In order to see the extent to which orbit correction is influenced by a particular distribution of dipoles in the ring we looked at 10 different distributions of skew harmonics generated randomly according to the values given earlier in the report. The method we used to do this was as follows: taking the values of the correction elements obtained from the systematic skew fields, and making no attempt to optimize these values for a given distribution of dipoles, we looked at the change in the vertical orbit amplitude for the different dipole distributions. The average increase in vertical amplitude was 0.8 mm. This value is consistent with an estimate of the amount of 0th and 39th harmonic produced by a random distribution of the dipole skew quad term. These results indicate a possible need for a series of correction elements distributed on the 39th harmonic as well as the zeroth harmonic.

With the presence of skew fields coupling the horizontal and vertical orbits a vertical dispersion fuction can be defined in an analogous fashion to the horizontal case. We have examined the vertical dispersion by looking at the horizontal and vertical closed orbits as a function of momentum offset for several different distributions of dipoles. The results show that in the range of momentum we covered ($\Delta p/p \leqslant 0.3\%$) the vertical dispersion function remains constant with η max = 0.5 ± 0.1 m. This value does not change significantly when the skew correction elements are turned on, and it is consistent with a theoretical estimate (0.48 m) made by S. Ohnuma in UPC No. 103.

Provided that no major design changes are made to the dipoles then it appears from the present magnet data that the major source of orbit coupling will arise from the skew quadrupole field in the dipoles. With this fact in mind we have looked at the effects of changing the systematic value of this skew field. Using only this systematic term for the dipole skew field, and correcting skew quadrupoles at each standard cell, we adjusted the values of the correcting elements so as to minimize the vertical orbit amplitude during the extraction cycle. The results obtained are summarized in Fig. 1 where we have plotted vertical orbit amplitude at a standard cell (β = 100) versus dipole skew quadrupole harmonic. It is apparent that there is a linear relationship between the dipole skew quadrupole coefficient and how well we can correct the vertical orbit. To rephrase this slightly: as the dipole skew field increases, turning up the strength of the correction elements does not completely cancel out the effect of these skew fields. It is therefore important to attempt to minimize this harmonic component during the construction of the dipoles if possible.

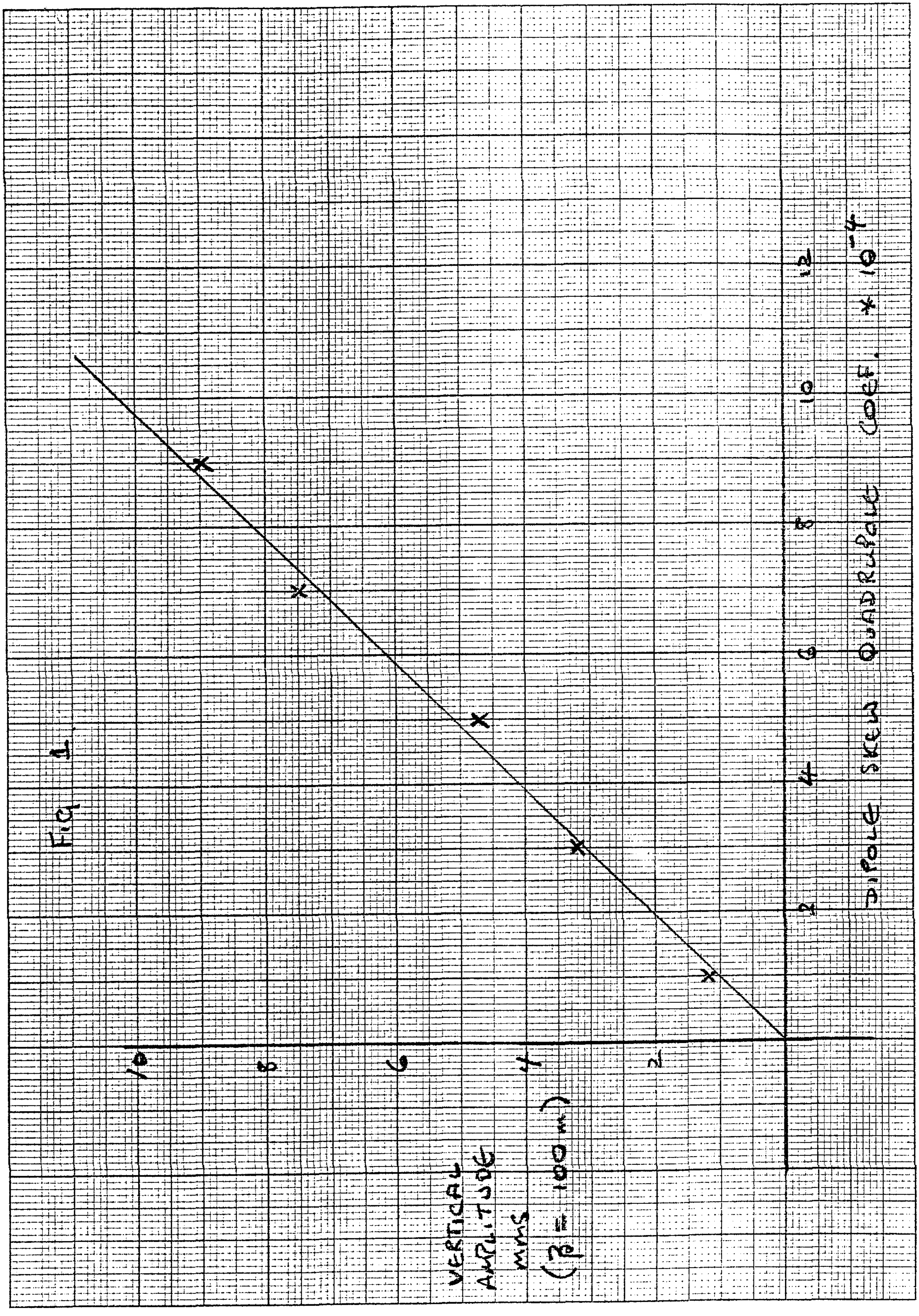
FIG 1
DIPOLE SKEW QUADRUPOLE COEF. * 10^-4
2
4
6
8
10
12
VERTICAL AMPLITUDE MMS (β = 100 m)
2
4
6
8
10